Ultra-Low Noise HEMT Device Models: Application of On-Wafer Cryogenic Noise Analysis and Improved Parameter Extraction Techniques

J.J. Bautista
Jet Propulsion laboratory, California Institute of Technology
Pasadena, CA 91109-8099

M. Hamai, M. Nishimoto and J. Laskar
Electrical engineering Dept., University of Hawaii
483 Holmes Hall, Honolulu, Hawaii 96822

P. Szydlik
Physics Department, State University of New-York-Plattsburgh
Plattsburgh, New York

R. Lai
TRW Electronic Systems and Technology Division
Redondo Beach, CA 90278

Abstract

Significant advances in the development of HEMT technology have resulted in high performance cryogenic, LNAs whose noise temperatures arc within an order of magnitude of the quantum noise limit (hv/k). Key to the identification of optimum HEMT structures at cryogenic {temperatures is the development of on-wafer noise and device parameter extraction techniques.

Introduction

The noise and gain of HEMT devices have steadily improved as the technology is developed and commercialized for room temperature applications. In order to successfully develop ultra-low noise, cryogenic HEMTs one must develop an accurate, repeatable data base of cm-wafer cryogenic noise results coupled with detailed parameter extraction techniques.

A cryogenic on-wafer noise and scattering parameter measurement has been developed [1] to provide a systematic investigation of HEMT noise characteristics. In addition, an improved parameter extraction technique has been developed to help understand the relationship between device structure and LNA performance.

Experimental Technique

Over the past several years the development of a complete on-wafer cryogenic microwave measurement system has been driven primarily by: (1) a need for greater understanding of the device physics in advanced high speed transistor technologies and (2) the continued advancement of cryogenic, LNA technology with noise temperature less than five times the quantum limit for ground and space-based applications.

Though on-wafer S-parameter measurement systems have been implemented to various degrees of success by several groups, no comprehensive or convincing results have been presented for on-wafer, cryogenic noise results [2 - 4]. For the most accurate and repeatable noise parameter measurements at cryogenic temperatures the impedance generator and noise source must be within a wavelength of the DUT input. in addition, the equivalent noise temperature of the noise source must also be comparable to the DUT noise temperature. In this investigation, only the microwave probe heads are cooled and are interfaced with commercially available solid state noise source and impedance generator. Although this configuration does not provide the most accurate single frequency data, it does provide a technique for rapid extraction of the noise performance versus temperature. The noise calibration must pass all the S-parameter calibration criteria and accurately measure the minimum noise temperature (T_{min}) and the associated gain (G_A) of a 10 dB attenuator. Our experiments are repeatable to within ± 5% for the attenuator at a variety of temperatures.

Parameter Extraction Techniques

A variety of HEMT structures have been investigated to determine the temperature behavior of both the intrinsic and extrinsic device parameters. The structures investigated include: AlGaAs/GaAs HEMT (conventional), AlGaAs/InGaAs pseudomorphic HEMT (PHEMT) and lattice matched InAlAs/InGaAs HEMT (InP HEMT).

A HEMT parasitic model has been developed, see Fig. 1, based upon the results in [5 - 8]. This model accounts for bias dependent resistances which affect the parasitic resistances (R_s, R_g and R_d) as a function of gate-source bias with V_{ds}=0v. The intrinsic and extrinsic parameters can be extracted using the equations presented by [5], conventional Hot/Cold FET techniques and the basic model in [8]. One major modification has been the removal of the depletion capacitance cited in [8] resulting in a symmetric parasitic model.

This Hot/Cold FET analysis has been applied to several different HEMT structures. We demonstrate excellent agreement between measured and model data at cryogenic temperatures as shown in Fig. 2. A summary of typical results for the conventional PHEMT and InP HEMT are shown in Table 1. The InP HEMT shows the greatest variation with temperature, primarily due to a higher electron mobility. Two of the most important parameters for extraction are the source resistance, R_s, and inductance, Ls. These terms must be accurately extracted since they serve as a feedback term in device operation.

Cryogenic, On-Wafer Noise Results

The development of an accurate HEMT device model allows us to predict the behavior of Γ_{opt} and T_{min} as a function of frequency. Based upon the direct measurement of the cryogenic noise parameters, cryogenic S-parameters and the room temperature device model we can extract a complete temperature dependant device model. We directly measure the noise parameters at cryogenic temperatures and correlate with the predicted performance based upon the model presented in [9]. All four noise parameters could not be reliably measured for the physical temperature and frequency spans of interest. A plot comparing the measured and modeled Γ_{opt} values at room temperature is shown in Fig. 3., while Fig. 4. shows the correlation of noise temperatures for measured and modeled values at cryogenic temperatures.

Conclusion

The feasibility of cryogenic, broadband on-wafer scattering and noise parameter measurements for the systematic investigation of HEMT noise characteristics has been demonstrated, In addition, an improved parameter extraction technique has been developed to help understand the relationship between device structure and LNA performance,

Future development of a coolable noise and impedance generator, integrable with the cryogenic, microwave probe that is capable of performing broadband scattering and noise parameter measurements will circumvent the limitations posed by the current characterization techniques. An integrated probe will enhance the fundamental study of noise sources in solid state technology and lead to improved cost and performance benefits for HEMT cryogenic technology.

References

[1] J. Laskar, et. al., 1994 Microwave Theory and Techniques Conference, San Diego, p. 1485 (May 1994).

[2] S. R. Taub, et. al., 43rd ARFTG Conference, p. 34 (May 1994).

[3] H. Meschede, et. al., IEEE Trans., Microwave Theory Tech., vol. 40, p.2325, (1992).

[4] T. Mizutani and K. Maezawa, IEEE Electron Dev. Lett., vol. 13, pp. 8-10, (1992).

[5] M. Golio, et al., Microwaves & RF, pp. 67-73, (October 1992).

[6] M. Berroth, et al., IEEE Transactions on Microwave Theory and Techniques, vol. 38, no. 7, pp. 891-895, (July 1990).

[7] G. Dambrine, et. al., IEEE Transactions on Microwave Theory and Techniques, vol. 36, no. 7, pp. 1151-1159, (July 1988).

[8] P. White, et. al., IEEE Microwave and Guided Wave Letters, vol. 3, no. 12, pp. 453-454, (December 1993).

[9] M. Pospiezalski, IEEE Transactions on Microwave Theory and Techniques, vol. 37, (1989).

Acknowledgements

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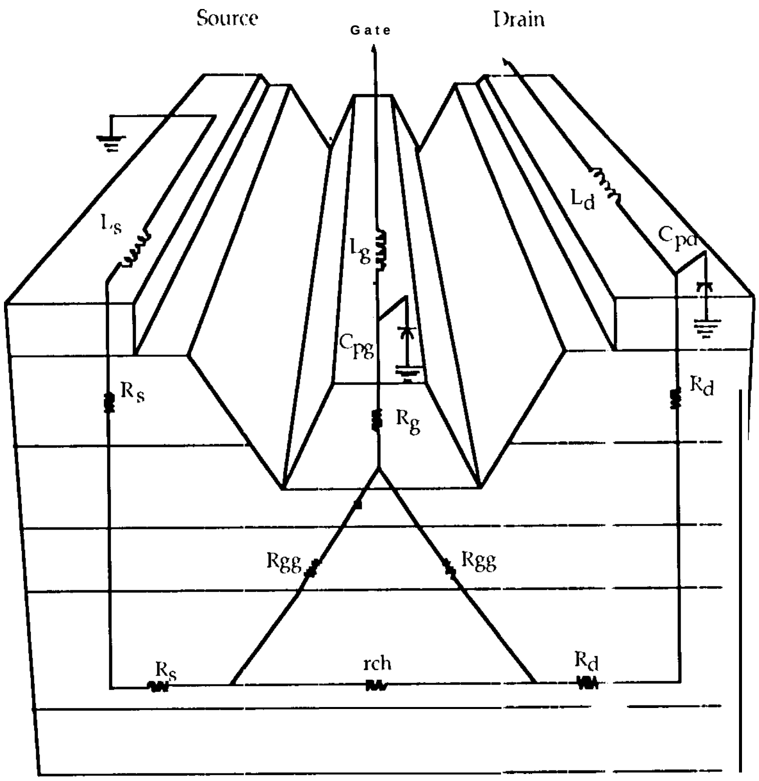

Fig. 1 Schematic model for HEMT parasitic element extraction

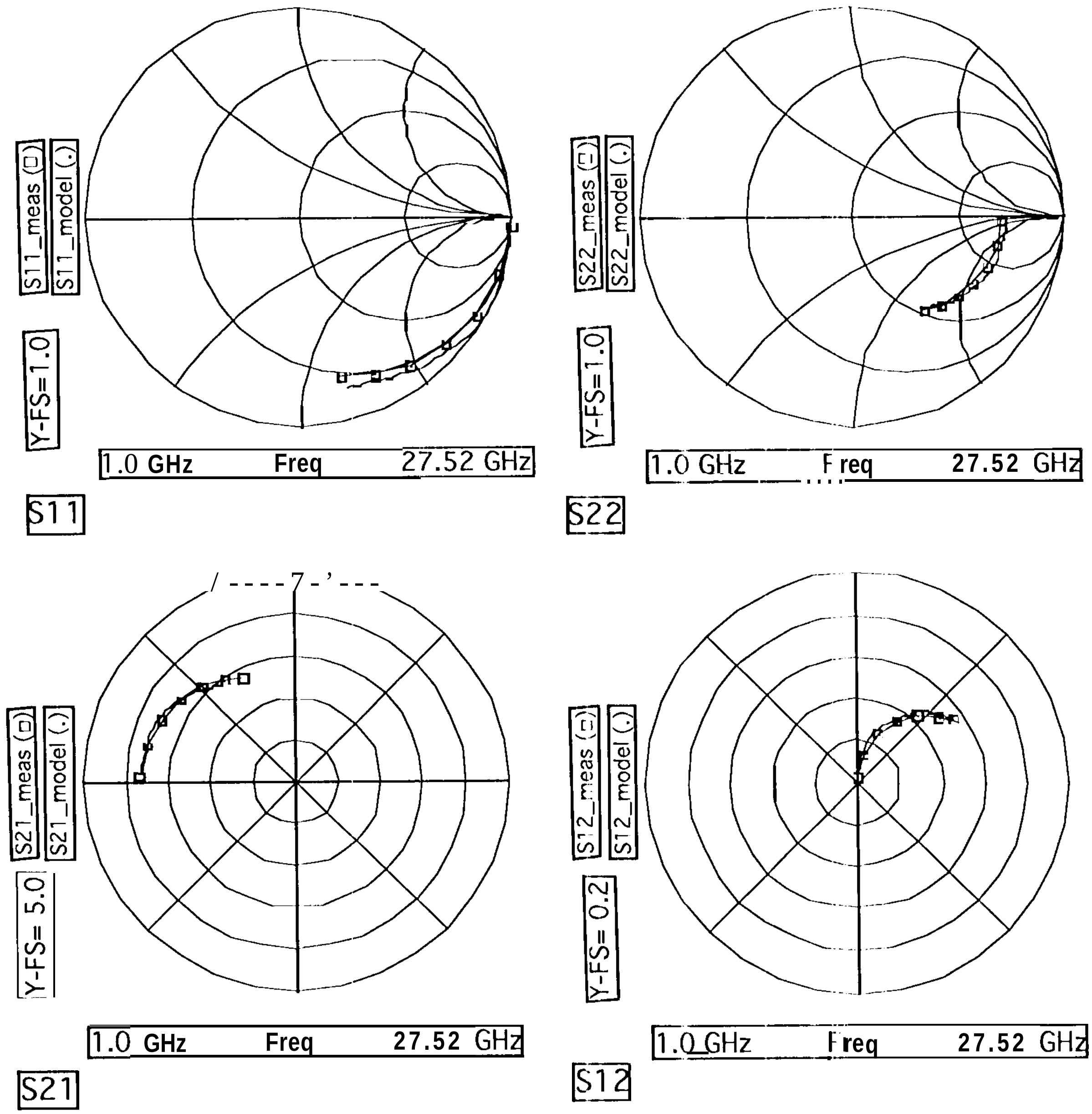

Fig. 2 Measured and modeled S-parameters for AlGaAs/InGaAs PHEMT structure biased at 100% Idss at a temperature of 16K. The model element values are determined using a modified Hot/Cold FET extraction technique with no optimization of parameters.

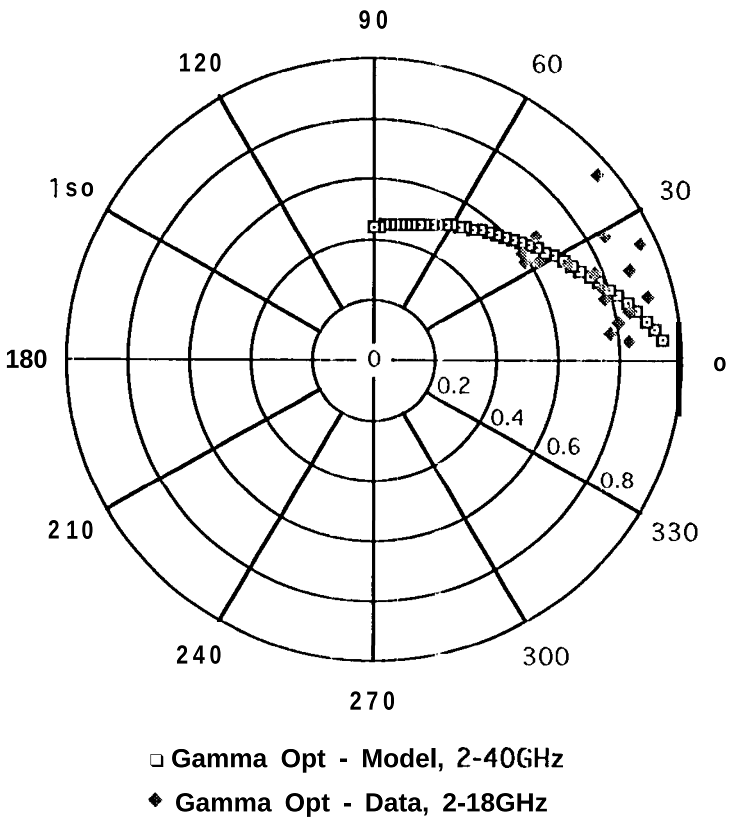

Fig. 3 Comparison of measured (2-18GI Iz) and modeled Γ_{opt} (2-40GHz) from for PHEMT at room temperature.

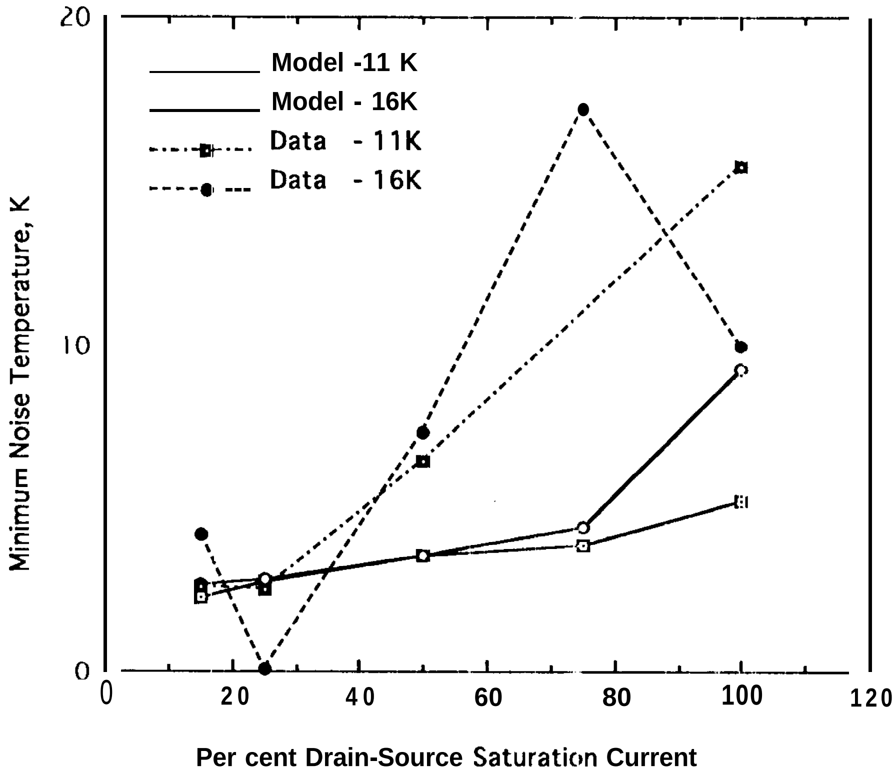

Fig. 4 Measured and Modeled values of T_{min} at a frequency of 18 GHz at 11 K and 16K.

Table 1 Extracted Smal -Signa] element values at 300K and 16K using modified Hot/Cold FET extraction.

PHEMT	300K	16K
Lg (pH)	28.3	39.4
Ld (pH)	27.2	44.6
Ls (pH)	4.6	3.8
Rg (ohms)	15.3	12.4
Rd (ohms)	3.4	4.0
Rs (ohms)	0.6	0.8
Cpg (fF)	7.5	6.5
Cpd (fF)	3.2	12.2

InP HEMT 2x80	3001<	16K
Lg (pH)	13.5	23.8
Ld (pH)	4.5	25.5
Ls (pH)	0.3	0.2
Rg (ohms)	18.5	4.6
Rd (ohms)	4.6	1.0
Rs (ohms)	1.2	0.3
Cpg (fF)	1.2	1.1
Cpd (fF)	1,4	1.1

MODIC FET6o	300K	16K
Lg (pH)	30.6	31.0
Ld (pH)	28.2	38.0
Ls (pH)	1.6	1.1
Rg (ohms)	12.4	9.9
Rd (ohms)	3.2	4.6
Rs (ohms)	0.7	0.9
Cpg (fF)	21.0	19.6
Cpd (fF)	10.0	17.8